COLLECTION OF AEROSOLS ON FIBER MATS

by

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The object of this work is to obtain a correlation between the collection efficiency of a fiber mat and the pressure drop across the mat. The mechanisms involved in the collection of aerosol particles in filters include gravity settling, inertial impaction, finite size interception, electrostatic attraction, and Brownian diffusion. At present, we are interested in isolating the inertial mechanism for study. Consider a fiber mat consisting of a large number of cylindrical fibers. If the aerosol particles passing into the mat have small diameters compared to the fiber diameters, the interception mechanism can be neglected. Electrostatic attraction can be eliminated by dealing with uncharged particles and fibers. Gravity settling is negligible for particles of the order of one micron moving at relatively high velocities. Brownian diffusion can be made insignificant if the particles do not have diameters smaller than half of a micron.

A fiber mat can be pictured as consisting of numerous cylinders randomly oriented. For cases where the volume occupied by the fibers is small compared with the overall volume of the mat, the collection efficiency should be the sum of the inertial impaction efficiencies of the single cylinders and the pressure drop should be the total drag force on these cylinders per unit area of the mat surface. For cases where the fiber volume is appreciable, a correction should be applied to the volumetric velocity of the aerosol stream if the inertial impaction efficiencies and total drag force on the single cylinders are to be used to predict the collection efficiency and the pressure drop, respectively, of the mat. Undoubtedly, in either case, there is a mutual effect of the fibers on each other, both in regard to the collection efficiency and the pressure loss. This may be expressed by modifying the Reynolds Number so that it includes a mutual interaction constant which depends on the geometry of the fiber mat. By defining a parameter representing the ratic of the velocity inside the fiber mat to the upstream volumetric velocity, we have worked out equations relating the collection efficiency to the pressure drop of the mat based on the drag coefficient and the inertial impaction efficiency for single cylinders. This parameter is unity when the fibers occupy a negligible volume. In deriving these equations, several simplifying assumptions were made.

Equipment is now being designed to measure simultaneously the inertial collection efficiency and the pressure drop of fiber mats specially made for the purpose of testing the validity of the basic assumptions. At this time, it suffices to note that the theoretical equations contain all the essential constants of the mat, such as fiber diameter, bulk density, fiber density, and mat thickness and that the parameter representing the velocity inside the mat to the upstream velocity can be evaluated by experimental measurements. The parameter for inertial impaction is assumed to be the same as that for pressure drop. If these equations are valid, a measurement of the pressure drop across a fiber mat can be used to predict the inertial collection efficiency of the mat, or vice versa. What is more, since the inertial mechanism is the only one that is directly related to the pressure loss, the correlation, in theory at least, should represent the minimum collection efficiency at a given pressure loss across the mat. To this correlation, the contributions of the other mechanisms, such as interception, Brownian diffusion, etc., to the collection efficiency of the mat can be added one by one.

We need to have reliable experimental data on inertial impaction efficiencies and drag coefficients of single cylinders. As far as the inertial impaction efficiency of single cylinders is concerned, experimental data are meager although the problem has been investigated rather extensively from the theoretical standpoint. The results expected from different theories are not always in agreement, and some experimental investigation is necessary. With regard to the drag coefficient on single cylinders, we have again found it advisable to take data in a range of the Reynolds Number where neither theory nor experiment has been adequate.

Inertial Impaction Efficiency on Cylindrical Collectors

Figure 1 is a schematic diagram of the experimental equipment used to establish the efficiency curves for inertial impaction on cylindrical collectors (1). A condensation aerosol was produced in a generator similar to that described by LaMer (6). The air at 90 pounds per square inch pressure and saturated with water vapor was filtered, but not dried, and metered through a pressure regulator to the humidifier and the salt nuclei generator; a side stream was used to dilute the dense aerosol from the reheater of the aerosol generator.

Concentrated sulfuric acid was used as the aerosol material. The concentration of acid in the aerosol droplets was nearly constant with a mean of 50.5 weight per cent in equilibrium with the moisture content of the expanded supply air. Although the moisture content of the supply air was relatively low, there was a great excess of moisture over that needed to form the fog. As a result, the aerosol particles did not change in size when additional air of practically the same humidity was added, and the aerosol velocity through the test section could be varied without changing the particle size.

A 3-mil platinum wire was used as the cylindrical collector. The wire was wound on a drum which could be rotated by a knob attached to it. Below the drum, a Venturi-shape nozzle having a throat diameter of 0.125 inch and fabricated of polystyrene was installed with its center line in a horizontal plane. The wire passed vertically downward across the mid-section of the throat into an 8-mm. glass wash tube about 4 feet in length. To facilitate introduction and removal of wash water, a side arm was attached near the top of the glass tube, and a stopcock was connected to the lower end. A filter train consisted of three separate filters, each containing about 1 inch of tightly packed No. 800 Pyrex brand glass wool, was used to collect the aerosol particles which escaped impaction on the wire. The filters could be removed and weighed. As all, or nearly all of the weight increase appeared in the first two sections, complete removal of the particles was assumed.

The aerosol stream could be directed through the equipment by five different paths: (1) discarded through the aspirator when the generator was being adjusted to produce a steady flow of a homogeneous aerosol of the desired particle size, (2) discarded into the vacuum system filter so as to establish steady conditions at the two-way quick-opening valve, (3) sent through the jet impactor for analysis for acid concentration, (4) sent through the optical system (the "Owl") for measurement of the particle size, and (5) during test runs, directed by the two-way valve through the nozzle passing the cylindrical collector into the filter train. The amount of aerosol collected on the wire was determined by washing with a measured amount of conductance water and finding the change in conductivity.

Figure 2 shows in graphical form the results of the experimental measurements. Here C is Cunningham's correction for small particles, ρ_p is the density of the particle, v_o is the volumetric velocity of the fluid stream, μ is the viscosity of the fluid, D_c is the diameter of the cylindrical collector, D_p is the diameter of the aerosol particles, and η is the target efficiency of collection. The ranges of variables studied are: particle diameters, 0.36 to 1.30 microns; relative velocity of the aerosol stream, 2000 to 7000 cm. per second; and particle concentration, approximately 10^5 to 10^7 particles per cc. As the ratio of particle diameter to collector diameter was never greater than 0.02, collection by interception was considered negligible. Brownian diffusion had little effect under the existing velocities and particle sizes. Since the particles were not charged, collection by the electrostatic mechanism was also improbable. The results, therefore, should represent collection by the inertial impaction mechanism alone.

The experimental data confirm the general shape and relative position of the inertial impaction curves for cylindrical collectors predicted by the theoretical curves reproduced in Figure 3 (1). Because the experimental variables were difficult to control, it is perhaps more accurate to consider the curve as a confirmation of the theoretical calculations, which were based on assumed ideal flow around the cylindrical collector. The theoretical equations for impaction on a cylinder indicate the existence of a critical value of ψ below which impaction cannot occur. The calculated value of the intercept depends on the model assumed for the flow lines. While extrapolation of the experimental curve indicates that such an intercept may exist, there is no definite evidence of what the critical value of the parameter may be. Since this is a region of considerable practical importance, the studies are being continued with improved equipment in the hope that a more complete curve may be obtained and the existence or nonexistence of the critical value of ψ can be established definitely.

Drag Coefficient of Circular Cylinders

The drag coefficient of a small circular cylinder placed in a stream of fluid with its axis normal to the flow may be predicted for viscous flow by a theoretical equation derived by Lamb (2). Because of the simplifying assumptions made in its derivation, however, the equation can be applied only when the Reynolds Number is less than 0.1. In contrast to the corresponding Stokes equation for spheres, the Lamb equation has not been verified by experiment.

White measured the terminal velocity of wires falling through liquids, but the drag coefficients which he found did not agree with the Lamb equation because of wall effects (9). The drag coefficients have been measured directly at relatively high velocities by a number of workers (4,5,8). The data of Wieselsberger extend to a Reynolds Number as low as 4.1 but between 4.1 and 0.1, the values of the drag coefficient are uncertain. Consequently, when presenting graphs of the drag coefficient versus the Reynolds Number for cylinders, the usual practice has been to draw a smooth curve connecting the data of Wieselsberger with the line representing the

Lamb equation. Tomotika and Aoi have recently refined the derivation of Lamb so as to allow the prediction of drag coefficients up to a Reynolds Number of 4, but no data were available to confirm their calculations (7).

The experimental technique used in our laboratory in the determination of drag coefficients for cylinders was similar in principle to that used by Wieselsberger (8). A fine wire with a weight attached to its lower end was suspended as a pendulum in a uniform stream of air flowing at a known rate. The drag force was calculated from the measured deflection of the pendulum. Since the weight itself hung outside the air stream, the deflection was due entirely to the drag of the cylindrical wire.

The flow chamber consisted of a short Lucite tube having an inside diameter of 1.90 cm. A standard flow nozzle was connected at the upstream end of the chamber and the downstream end was open to the atmosphere. In order to make the measurements with a uniform velocity profile, the wire was suspended to a point only 2 mm. downstream from a 200-mesh screen placed across the throat of the nozzle. Ranz has shown that such an arrangement gives uniform velocity for a variety of flow conditions (3).

The top of the test wire was soldered onto a steel needle which served as a support, and which passed through a small hole, at the top of the Lucite tube. The wire itself extended down through a hole in the bottom of the tube and its lower end, weighted with a drop of solder, was protected from stray air currents by a small Lucite box. The essential parts of the apparatus are shown in Figure 4.

Deflections of the wire were observed with a microscope equipped with a 32 mm. objective and a calibrated micrometer eyepiece. The point of observation was either at the bottom of the Lucite tube or just below the tube where the wire entered the Lucite box. From the deflection of the wire, d, the length exposed to the air stream, L, and the weight of the solder, W, it was possible to calculate the drag force, F, from the formula.

$$F = \frac{2Wd}{L}$$

This equation is based on the fact that the wires were flexible and therefore exerted no residual moment of force at the point of suspension. The drag coefficient C_D is defined by the equation

$$C_D = \frac{2Fg_c}{\rho v_o^2 D_c L}$$

where g_c is Newton's Law conversion factor, ρ is the density of the fluid, and other symbols have the same meanings stated previously.

Three sizes of wires were used: tungsten wires, 4.1 and 6.5 microns in diameter, and chromel wire, 12.6 microns in diameter. The wires were examined under an electron microscope to determine their size and uniformity. The operations of cleaning, copper plating, and soldering the test wires were facilitated by the use of a jig which had been built to make probes for a hot-wire anemometer.

The range of air flows was from 20 to 730 cm. per second, and the observed deflections varied from 36 microns to 1 mm. The weight of solder attached to the wire was in every case so much greater than the weight of the wire that the latter could be considered negligible.

The experimental data of this study are shown in Figure 5, together with the data of Wieselsberger; also shown are the theoretical lines proposed by Lamb and by Tomotika and Aoi. The Lamb equation is confirmed for the upper region of viscous flow. At higher Reynolds Numbers, the present data lie slightly below the predictions of Tomotika and Aoi, but there is a smooth fit with the experimental results of Wieselsberger.

The scatter of the data is not considered excessive in the light of the experimental difficulties. Some of the abnormally high values of the drag coefficient may be accounted for by a slight kinking of the wire or by surface roughness, although efforts were made to avoid such interferences. Since the diameter of the flow chamber was 1500 times the diameter of the largest wire used, any influence of the wall can be considered negligible.

Acknowledgment

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Literature Cited

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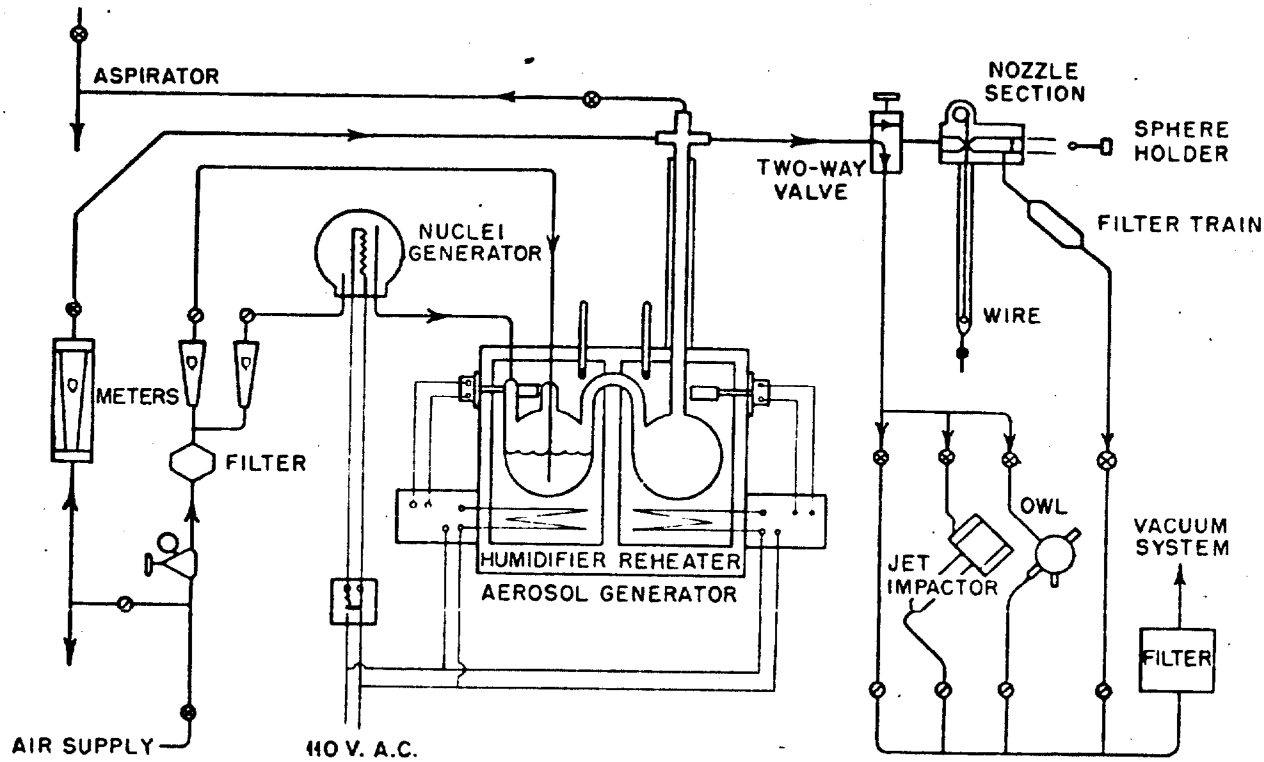

Fig. 1 — Experimental equipment, impaction on body collectors.

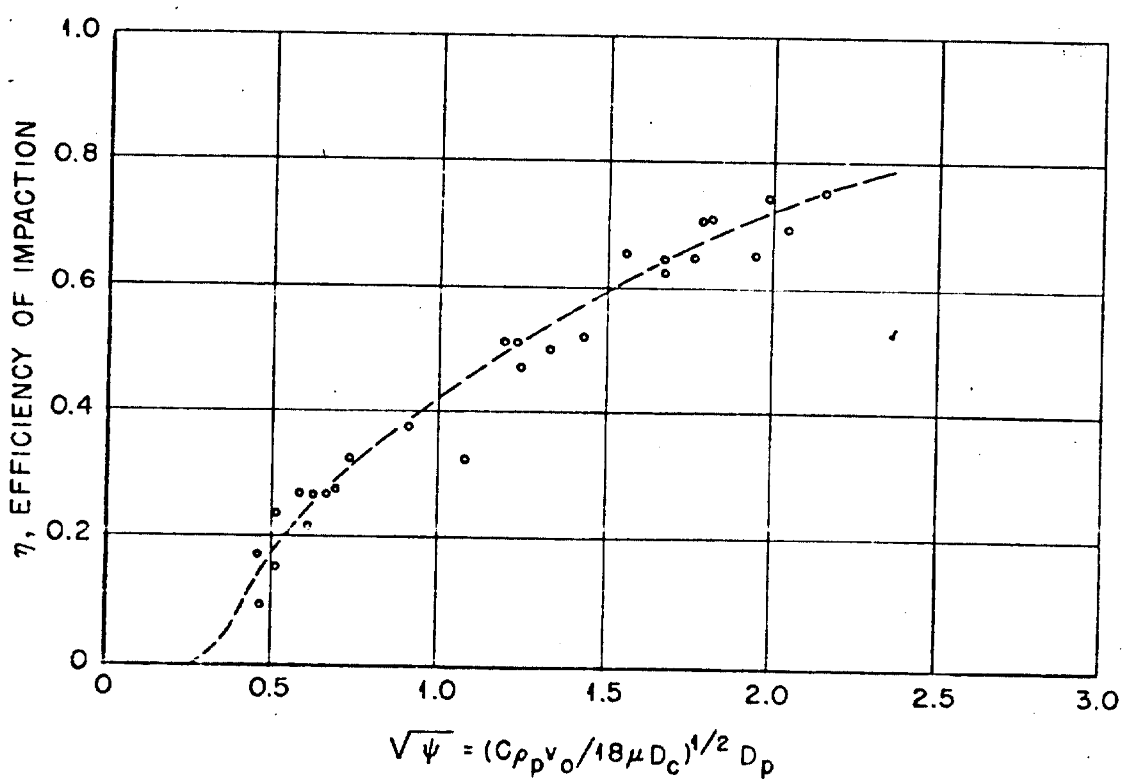

Fig. 2 — Experimental impaction efficiencies, cylindrical collectors.

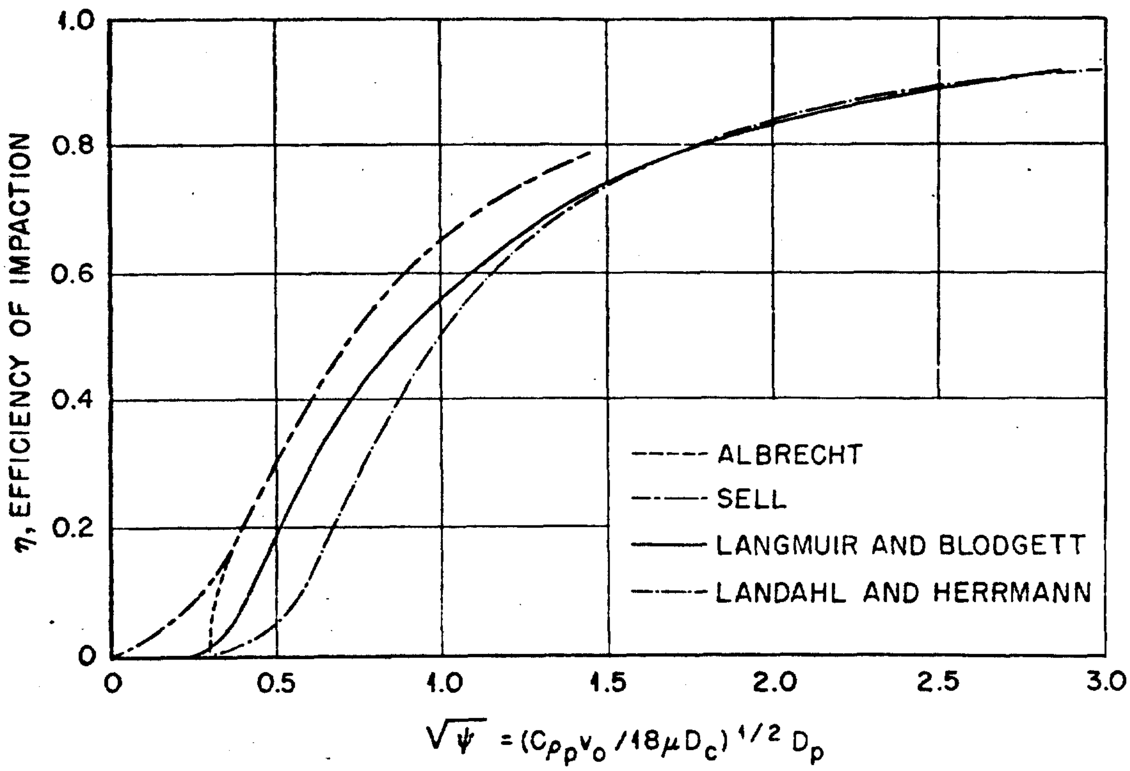

Fig. 3—Theoretical impaction efficiencies, cylindrical collectors.

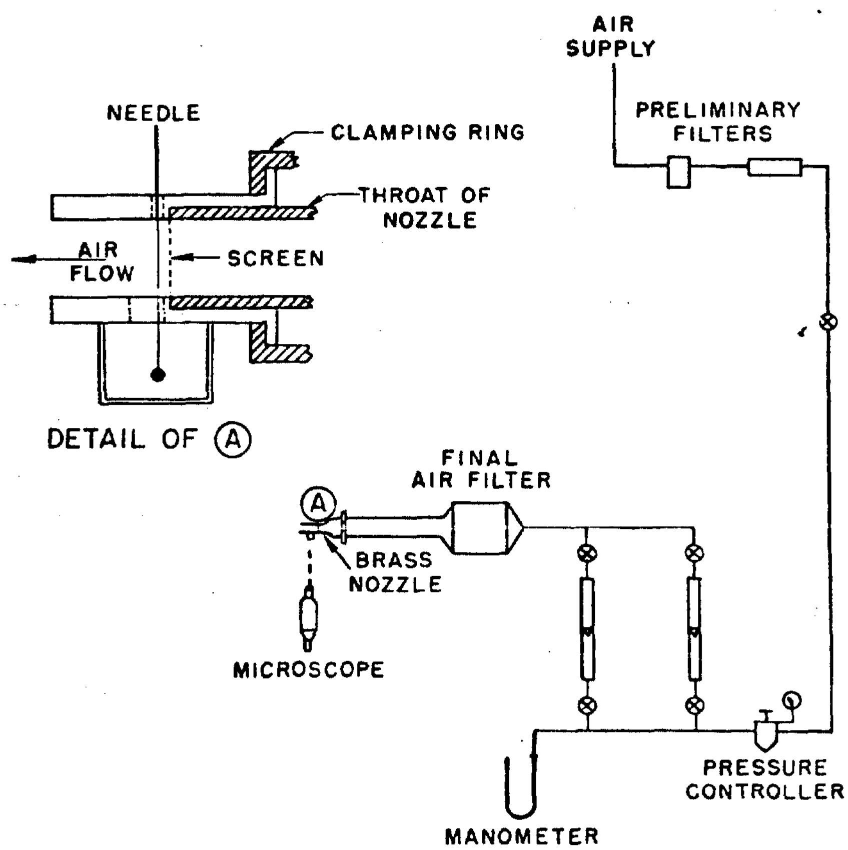

Fig. 4—Equipment for drag coefficients.

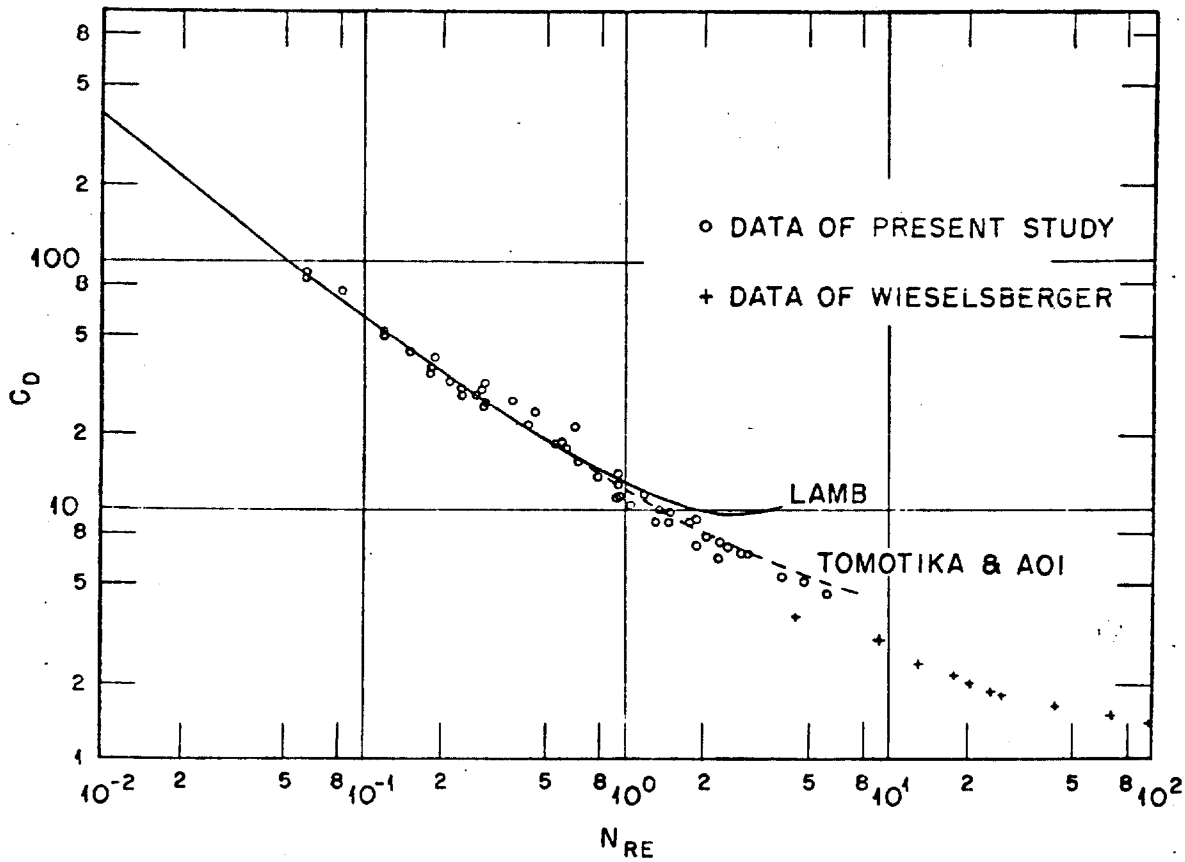

Fig. 5 — Experimental data, drag coefficients.